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Acehnese Reefs in the Wake of the Asian Tsunami

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Summary

The Sumatra-Andanaman tsunami was one of the greatest natural disasters in recorded human history. Here, we show that on the northwest coast of Aceh, Indonesia, where the tsunami was most ferocious [1], the damage to corals, although occasionally spectacular, was surprisingly limited. We detected no change in shallow coral assemblages between March 2003 and March 2005, with the exception of one site smothered by sediment. Direct tsunami damage was dependent on habitat and largely restricted to corals growing in unconsolidated substrata, a feature unique to tsunami disturbance. Reef condition, however, varied widely within the region and was clearly correlated with human impacts prior to the tsunami. Where fishing has been controlled, coral cover was high. In contrast, reefs exposed to destructive fishing had low coral cover and high algal cover, a phase shift the tsunami may exacerbate with an influx of sediments and nutrients [2]. Healthy reefs did not mitigate the damage on land. Inundation distance was largely determined by wave height and coastal topography. We conclude that although chronic human misuse has been much more destructive to reefs in Aceh than this rare natural disturbance [3], human modification of the reef did not contribute to the magnitude of damage on land.

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Results and Discussion

The earthquake of December 26, 2004 generated in Aceh a tsunami that consisted of at least three main waves (a wave train), preceded by an initial draw down [4]. The first wave was estimated at 12 m by eyewitnesses before it broke on the reefs on the Acehnese coast. The second wave was considerably larger, with flow heights at the coast ranging from 10.0 to 15.0 m [5]. Less than 100 days after the tsunami, we visited 17 sites on coral reefs in northern Aceh (Figure 1), all located within 300 km of the epicenter of the earthquake. Five of these sites had also been visited in March 2003, presenting a unique opportunity to asses the ecological impact of tsunamis on tropical marine ecosystems.

A comparison of the shallow-water (less than 2 m depth) coral assemblages from three sites on Pulau Weh (sites 8, 10, and 11, Figure 1) between March 2003 and April 2005 indicated no differences in the mean cover of ten coral taxa (Figures 2, 3A, and 3B); cover estimates were higher in most taxa posttsunami, and mean total hard coral cover was 43.0% ± 3.87 standard error (SE) in March 2003 and 47.0% ± 3.57 SE in March 2005. Although quantitative data on the abundance and composition of shallow coral assemblages were available from before the tsunami from only these three sites, estimates of direct damage to shallow colonies in this habitat were uniformly low throughout the region: Very few colonies were overturned or had been killed recently, although some colonies had broken branches (Figure 3C). In addition, a comparison of the reproductive status of *Acropora* corals [6] indicates that the tsunami did not prevent these colonies from breeding. Whereas the proportion of colonies breeding in March 2003 was slightly lower than in March 2005 (53% compared to 44%), the fraction of *Acropora* species breeding was similar (14 of 24 species sampled in March 2003 versus 15 of 24 in March 2005).

Direct effects of the tsunami were highly dependent on habitat and largely restricted to colonies growing in unconsolidated substratum on the reef slope. Corals firmly attached to solid substratum were largely unaffected by the force of the waves at all sites: Damage to these colonies included occasional broken branches (Figure 3C), presumably as a result of impacts with mobile debris, but very few colonies were dislodged. In contrast, corals growing in unconsolidated substrata, such as sand or rubble, suffered much greater damage: In these habitats, many colonies were overturned (Figure 3D), buried (Figure 3E), or transported, often over large distances (Figure 3F). Within habitats, damage was patchy and clearly influenced by reef aspect and submarine topography, as reported for reefs in Thailand following the tsunami [7]. For example, the number of overturned colonies below 2 m at site 9, which lies just to the north of a narrow channel between a small island

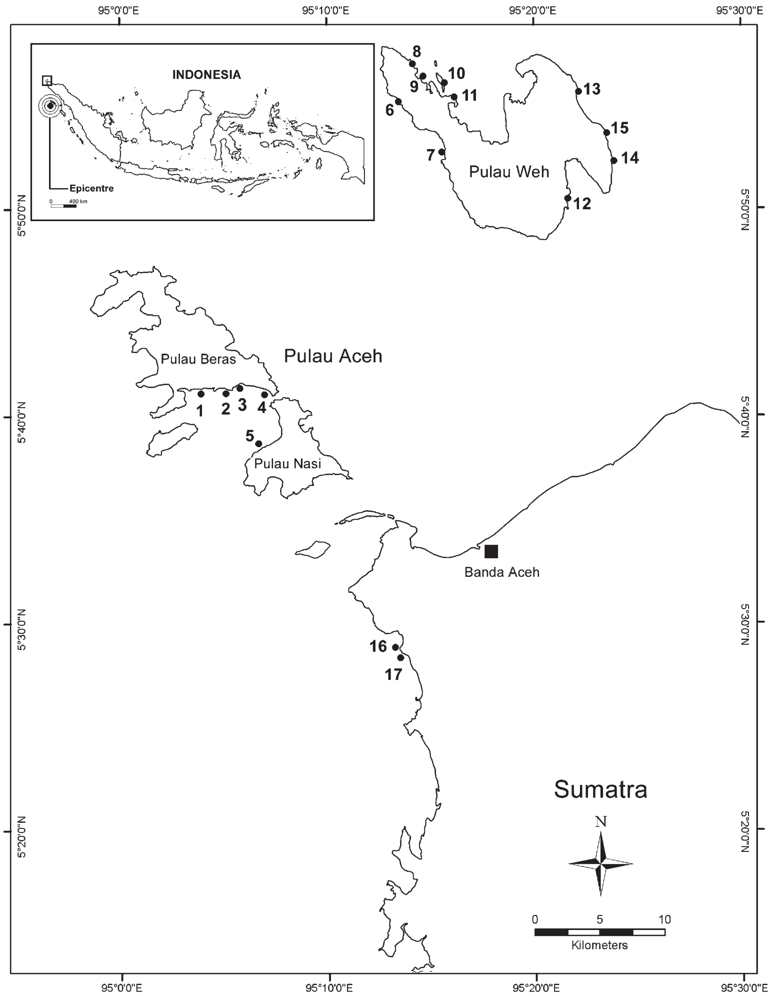

Figure 1. Map of Northern Aceh, Indicating the Location of 17 Sites Visited between March 31 and April 15, 2005

The epicentre of the December 26 earthquake is also indicated.

and Pulau Weh, was much higher than at site 10, which is on the open side of the small island (Figure 1). Similarly, the number of overturned colonies at depth was low at sites on the western side of Pulau Weh, where tsunami intensity, as measured by flow heights on land [8], was lower than elsewhere in the region. Despite this damage at depth, where coral assemblages were healthy prior to the tsunami, coral cover remained high, and there was little apparent loss of ecological diversity or function.

This type of damage is very different from that observed following large storms, such as hurricanes. Although hurricane damage to reefs is also patchy [9] and shallow reef areas do not necessarily suffer greater damage than those at depth [10], it is unusual for shallow reefs to escape damage on a large scale following hurricanes [11]. Furthermore, fragile morphologies, such as branching and tabular corals, are generally disproportionately affected when compared to massive colonies following hurricanes [9, 11]. A number of features of tsunamis are relevant for explaining this difference. In wind waves, most energy is contained near the surface, and wave-induced water motion diminishes exponentially with depth [12]. In contrast, in a tsunami, water is in motion throughout the entire water column [12]. We hypothesize that the initial run-down of the tsunami, along with the first wave of the tsunami train, excavated unconsolidated substrata from around the bases of unattached colonies, making them susceptible to displacement when inundated by the subsequent waves (Figure 3E). These observations are also consistent with predictions that the susceptibility of a colony to displacement is dependent on the strength of its attachment to solid substratum, rather than the size or shape of the colony or the intensity of the wave [13]. The differential damage to unattached massive colonies at depth appears to be a unique feature of tsunami disturbance and explains the dominance of massive colonies in tsunami deposits on land [14, 15].

The reefs of northern Aceh did not appear to have been damaged by earthquakes. Whereas reefs on the northeast coast of Simeleue, 300 km to the south of our study sites, were uplifted between 1 and 2 m following the earthquake of December 26, 2004 [16], in northern Aceh, the coast experienced subsidence. For example, the shoreline near Banda Aceh retreated up to 1.5 km inland through a combination of subsidence and erosion [5]; however, specific measures of subsidence in

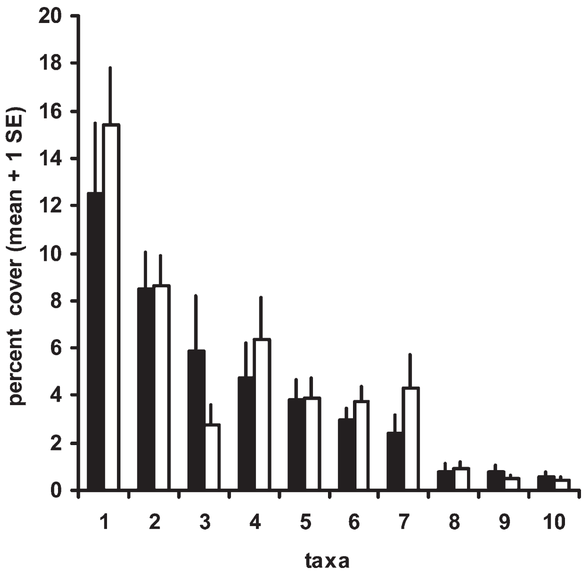

Figure 2. Shallow Hard Coral Assemblage Structure before and after the Tsunami in Aceh

Bars are the mean percent cover of five morphological categories of *Acropora* (1 = tabular; 2 = digitata; 3 = arborescent; 4 = arborescent tables; 8 = corymbose), and five taxonomic groups of other hard corals (5 = *Montipora*; 6 = Faviidae; 7 = *Porites*; 9 = other Scleractina; 10 = Pocilloporidae) on eight replicate 10 m line intercept transects run at less than 2 m depth at sites 8, 10, and 11 in Figure 1. Error bars are 1 standard error.

the region are yet to be published. Our observations under water in April 2005 and our familiarity with these reefs prior to December 26, 2004 lead us to conclude that at our sites there was no major reef-morphology change attributable to earthquakes.

Although the direct effects of the tsunami on shallow attached corals were relatively minor, changes in the sediment regime following the tsunami have caused localized coral mortality and continue to threaten some reefs. For example, on the southern edge of a fringing reef on the mainland (site 17, Figure 1), a previously flourishing *Acropora* assemblage has been smothered by sediments (Figures 3G and 3H). Surveys in March 2003 recorded 104 colonies from nine *Acropora* species in a 1 hr swim, whereas not a single live colony was found at this site in April 2005. Recently killed *Acropora* skeletons were still intact (Figure 3H), indicating that it was not direct physical disturbance that killed these colonies despite an estimated flow height for the tsunami of 10.0 to 15.0 m on the adjacent coast [5]. In contrast, the *Acropora* assemblage at the northern edge of this reef (site 16, Figure 1) was largely intact (49 colonies from ten species in March 2003 versus 41 colonies from eight species in April 2005). However, increased turbidity continues to threaten corals at other sites where some *Acropora* and faviids were bleached, probably as a consequence of prolonged periods of low light [17], because there is no indication of recent elevated sea surface temperatures in the area [18].

Reef condition varied widely within the region and was strongly influenced by controls on human activity (Figure 4). Hard coral cover at seven open-access sites (mean = 17.7% ±1.82 SE) was 40% of cover at sites in the Pulau Weh Marine Reserve (45.9% ± 2.33 SE) and only 28% of cover at sites where the traditional Acehnese management system, Panglima Laut, is practiced (61.7% ± 2.53 SE). Reef condition was particularly poor in Pulau Aceh (Figure 4), where long-dead colonies were covered with a thick growth of filamentous algae, scenes typical of reefs affected by bombing and cyanide fishing [19]. However, even here, where the tsunami was highly destructive on land, there was little evidence of recent coral mortality. Indeed, surveys of the distribution and abundance of coral colonies transported up to 120 m inland indicated that 83% were dead prior to being deposited onto land. The most likely cause of low cover and coral mortality in open-access sites is destructive fishing practices, such as bombing and cyanide fishing, both of which were prevalent throughout Indonesia in the recent past [20]. On Pulau Aceh, these practices have caused a phase shift from corals to algae, and the tsunami may have exacerbated this shift with an influx of nutrients. Few natural events can compare in scale and intensity to the Sumatra-Andaman tsunami, yet direct damage to reefs was surprisingly limited, and trivial when compared to the clear loss of coral cover where human access has been uncontrolled.

Recent reports, some relying largely on anecdotal evidence, have suggested that intact and healthy coastal environments, such as coral reefs, reduced tsunami damage in coastal communities [21–25]. Our observations in Aceh, where the tsunami was its most destructive, offer no support for this hypothesis. For example, a flourishing reef in front of the village of Lampuuk (sites 16 and 17, Figure 1) did not prevent the complete destruction of every structure in the settlement except the mosque. Similarly, the villages of Lampuyang, Lhoh, Pasi Janeng, and many others in Pulau Aceh were situated behind intact reefs, yet not one building was left standing in any of these villages and, consequently, any putative protective function was essentially meaningless. The limit of inundation at any particular location was determined by a combination of wave height and coastal topography and independent of reef quality or development prior to the tsunami. The wave stopped only when it reached the relevant inland contour, often up to 4 km inland [5]. Healthy coral reefs provide coastal communities with a range of valuable social and economic goods and services [26]; however, they cannot provide substantial protection from large tsunamis.

Acehnese reefs in the wake of the tsunami provide a profound example of the resilience of marine ecosystems to natural disturbance and also a powerful reminder of the potential for damage from chronic human misuse. The extent of the damage on land and the tragic human cost should not distract attention away from the perennial problems of marine resource management: improving water quality, reducing fishing pressure, and encouraging sustainable coastal development [27]. Neither the conservation priorities nor the risks to reefs have been changed by the tsunami, and it is vitally important that resources are not directed to short-term, small-scale rehabilitation programs, which

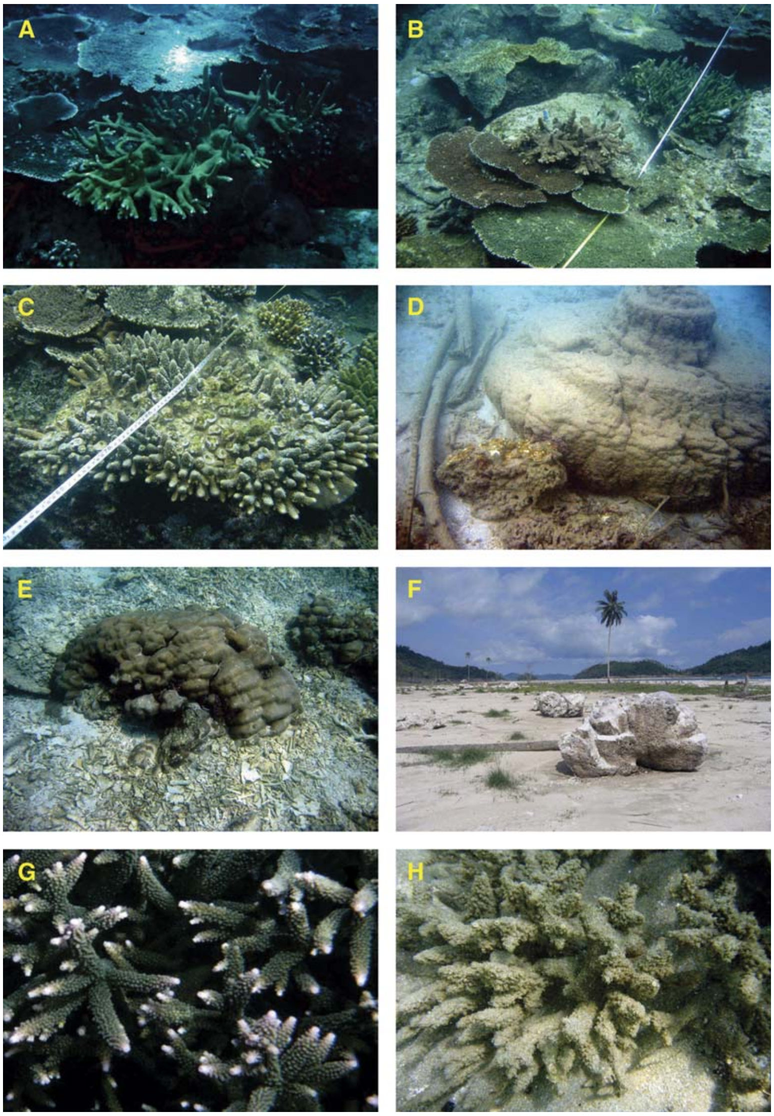

Figure 3. Hard Coral Assemblages in Aceh before and after the Tsunami, and Types of Tsunami Damage Observed

(A) Coral assemblage in 1 m at site 8, March 2003.
(B) Coral assemblage in 1 m at site 8, April 2005, showing no change in the assemblage following the tsunami.
(C) *Acropora gemmifera* colony at 1 m depth at site 9 with recently broken branches in the center of the colony, April 2005.
(D) An overturned *Porites* colony, 4 m in diameter, surrounded by a tree, in 6 m depth at site 16, April 2005.
(E) *Porites* colony 1.5 m in diameter half buried in rubble at 4 m depth at site 9, April 2005.
(F) Large *Porites* litter the coconut groves up to 50 m from the beach on Pulau Beras, April 2005.
(G) Flourishing colonies of *Acropora intermedia* in March 2003 at 1 m depth at site 17.
(H) The same colony in April 2005. The tissue has been smothered by sediment following the tsunami.

will not reverse long-term declines in reef condition [28]. The political goodwill and the financial resources the tsunami has generated should rather be used to build economies and societies that provide resilience in both the social and the ecological domain [29].

Experimental Procedures

Estimates of Coral Abundance

Coral cover was estimated at sites 1–15 by running 8–10 replicate 10 m line intercept transects [30], and the cover in cm of each scleractinian coral species was recorded. Species were then categorized into one of five morphological groups within the genus *Acropora* [31] and five further taxonomic groups (see Figure 2). Cover was then expressed as the percentage of 10 m covered by each group on each transect. One hour swims were conducted at sites 16 and 17 to estimate the number of *Acropora* colonies of each species. Sites 8, 10, 11, 16, and 17 were also visited in March 2003.

Reproductive Status of *Acropora* Corals

The reproductive status of each *Acropora* colony encountered in 1 hr swims at sites 8, 10, 11, 16, 17 in both March 2003 and March 2005 was determined by breaking up to three branches per colony to expose the developing eggs. Mature eggs in the *Acropora* are brightly pigmented and clearly visible against the white skeleton in broken branches [32].

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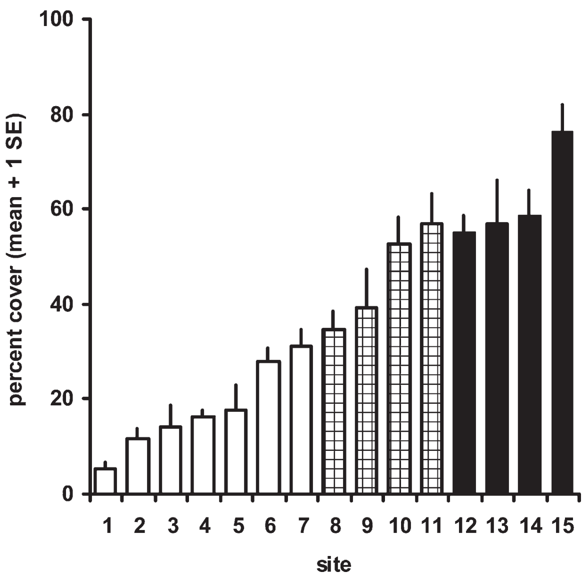

Figure 4. Hard Coral Cover at 0.5 to 2 m at 15 Sites on Pulau Weh and Pulau Aceh in March and April 2005

Bars are the mean percent cover of hard corals on eight replicate 10 m line intercept transects. Sites were located in areas with markedly different access regimes: open-access (open bars), Marine Reserve (hatched bars), and areas managed under the traditional Acehnese system, Panglima Laut (black bars). Error bars are 1 standard error.

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